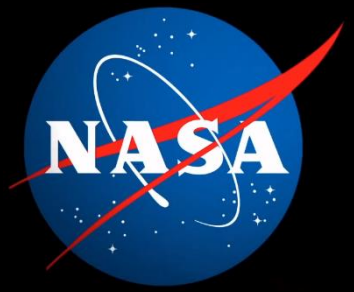
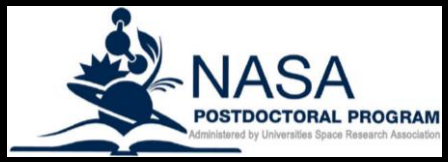
Modeling Diffuse X-ray Emission around the Galactic Center from Colliding Stellar Winds

arXiv:1607.01562



Christopher M. P. Russell
NASA
Goddard Space Flight Center



Q. Daniel Wang University of Massachusetts Amherst
Jorge Cuadra Pontificia Universidad Católica de Chile

Modeling Diffuse X-ray Emission around the Galactic Center

Modified version conducive to pdf format

→ movies converted to stills

For full talk with movies, see

http://asd.gsfc.nasa.gov/Chris.Russell/

Q. Daniel Wang University of Massachusetts Amherst

Jorge Cuadra Pontificia Universidad Católica de Chile

Observations – Chandra XVP

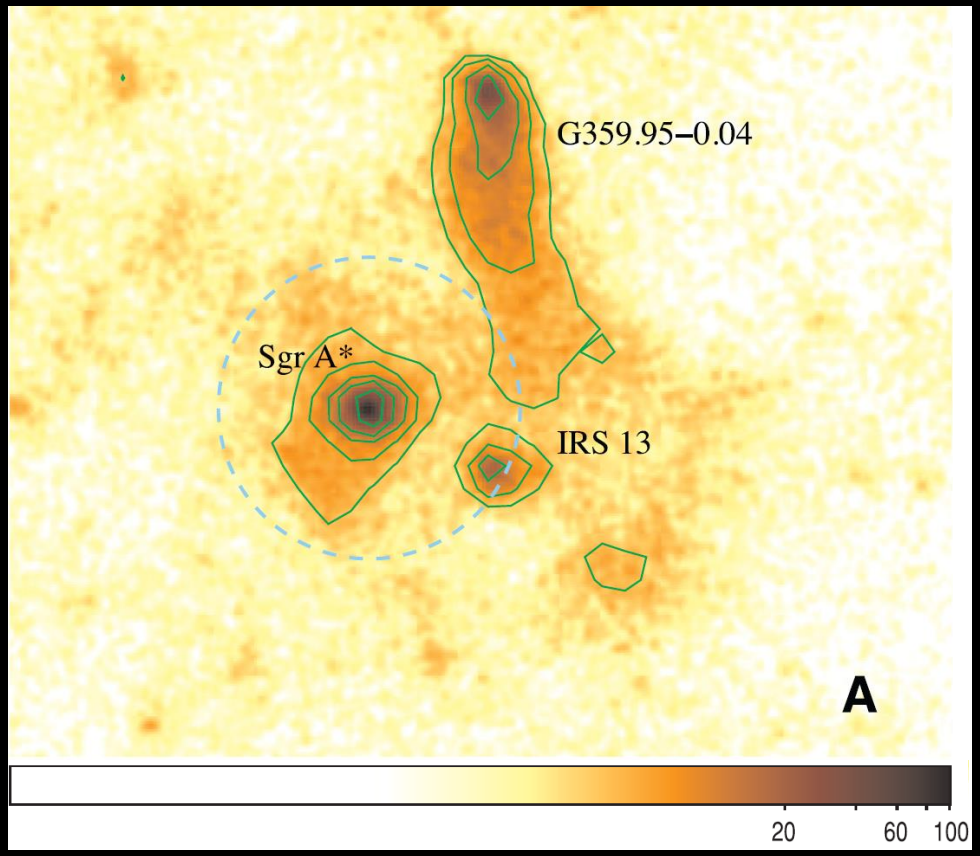
(Wang+13)

X-ray Visionary Program

- 3Ms
- Diffuse emission
- Emission from
  SMBH
  PWN G359

25”

20”



Chandra 0th Order ACIS-S/HETG
1-9 keV

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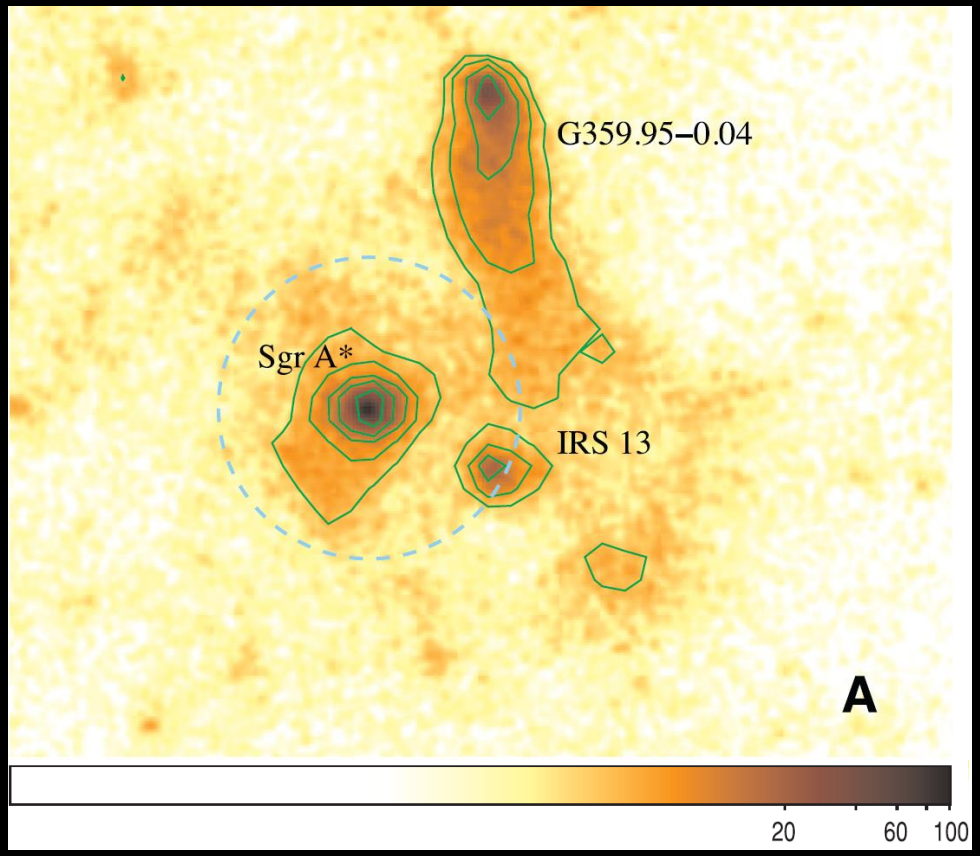

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Hydrodynamics - SPH (Cuadra+08)

smoothed particle hydrodynamics

- 30 Wolf-Rayet stars within 12” (~1 pc)
  - Orbits (except z) from IR monitoring (Paumard+06)
  - Wind properties from IR spectral fitting (Martins+07)
  - dM/dt ~ 0.5-10 x 10^{-5} M_{sun}/yr
    - Largest mass-loss-rate objects in vicinity
  - v_∞ ~ 600-2500 km/s
    - Shocks -> thermal X-rays

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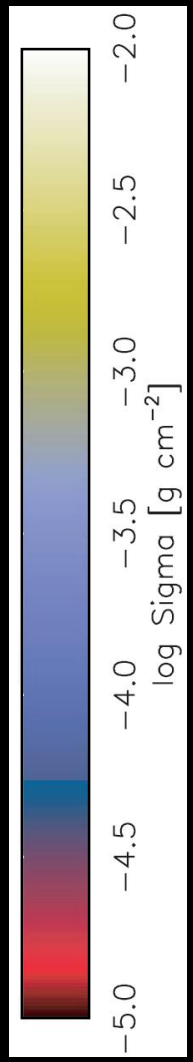
  - v_∞ ~ 600-2500 km/s
    - Shocks -> thermal X-rays
- Initial condition: run N-Body backwards 1100 yr
- Simulation: point masses (stars) eject SPH particles (stellar winds) over 1100 yr to present day
- Result: ρ & T structure in r<12” centered on SMBH

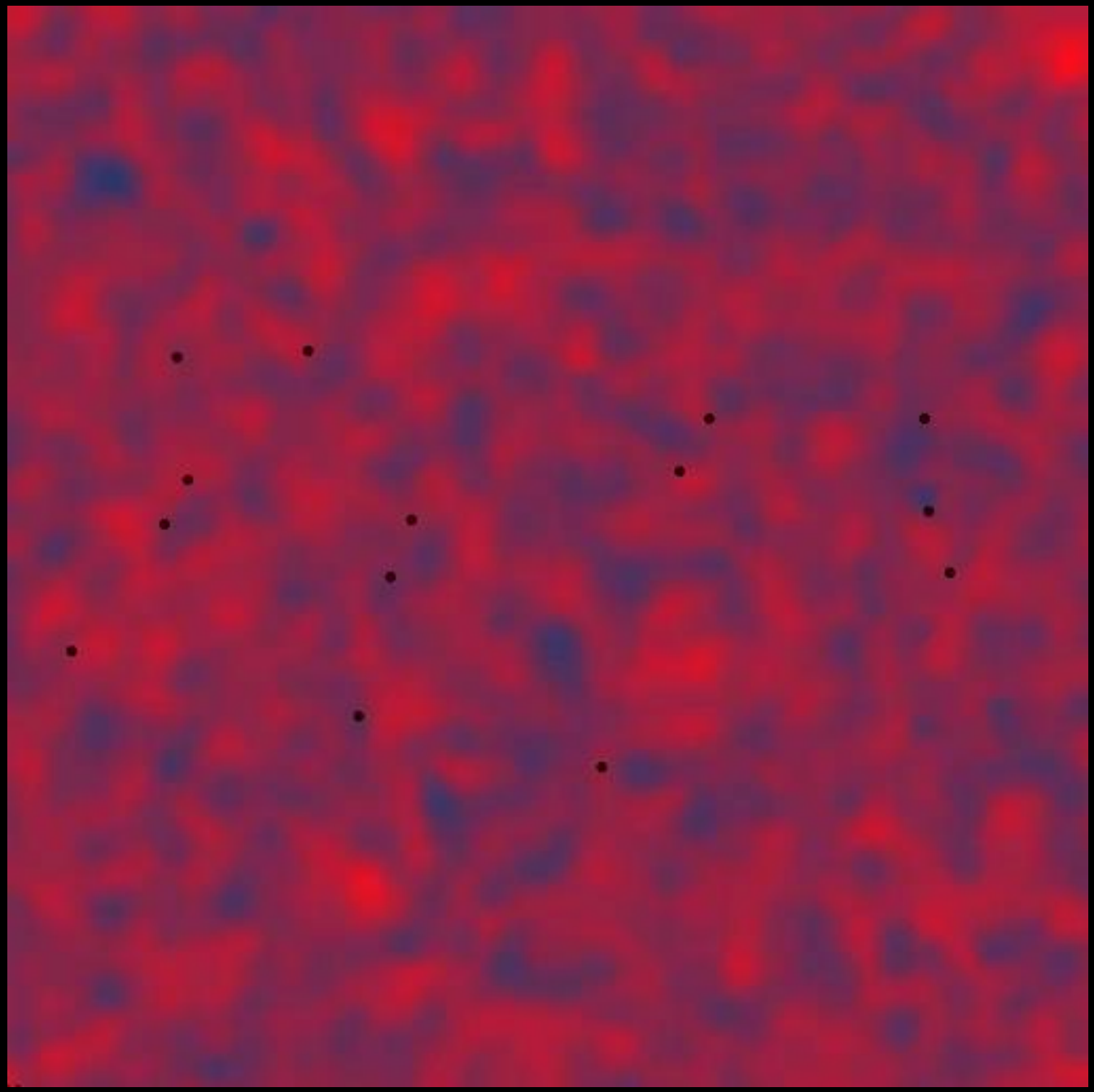
Movie frame: t=0 yr (1100 yr ago)

Column Density

(Cuadra+08)



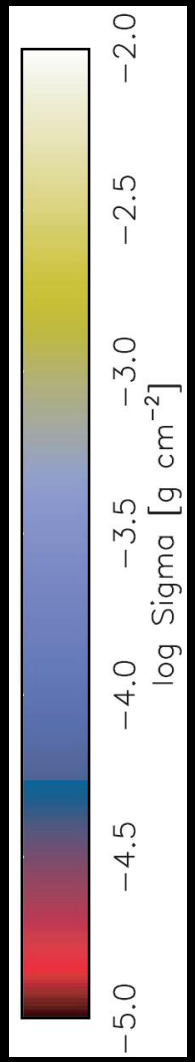
12x12”
~1x1 pc



Movie frame: t=100 yr (1000 yr ago)

Column Density

(Cuadra+08)

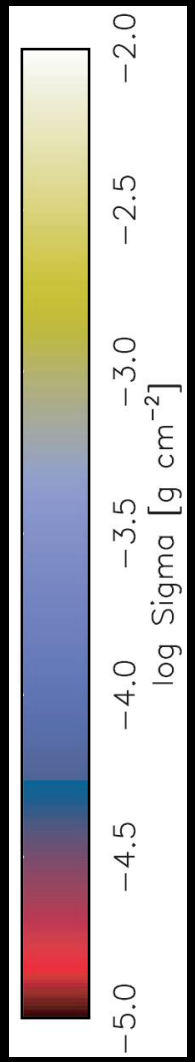


12x12”
~1x1 pc

Movie frame: t=200 yr (900 yr ago)

Column Density

(Cuadra+08)



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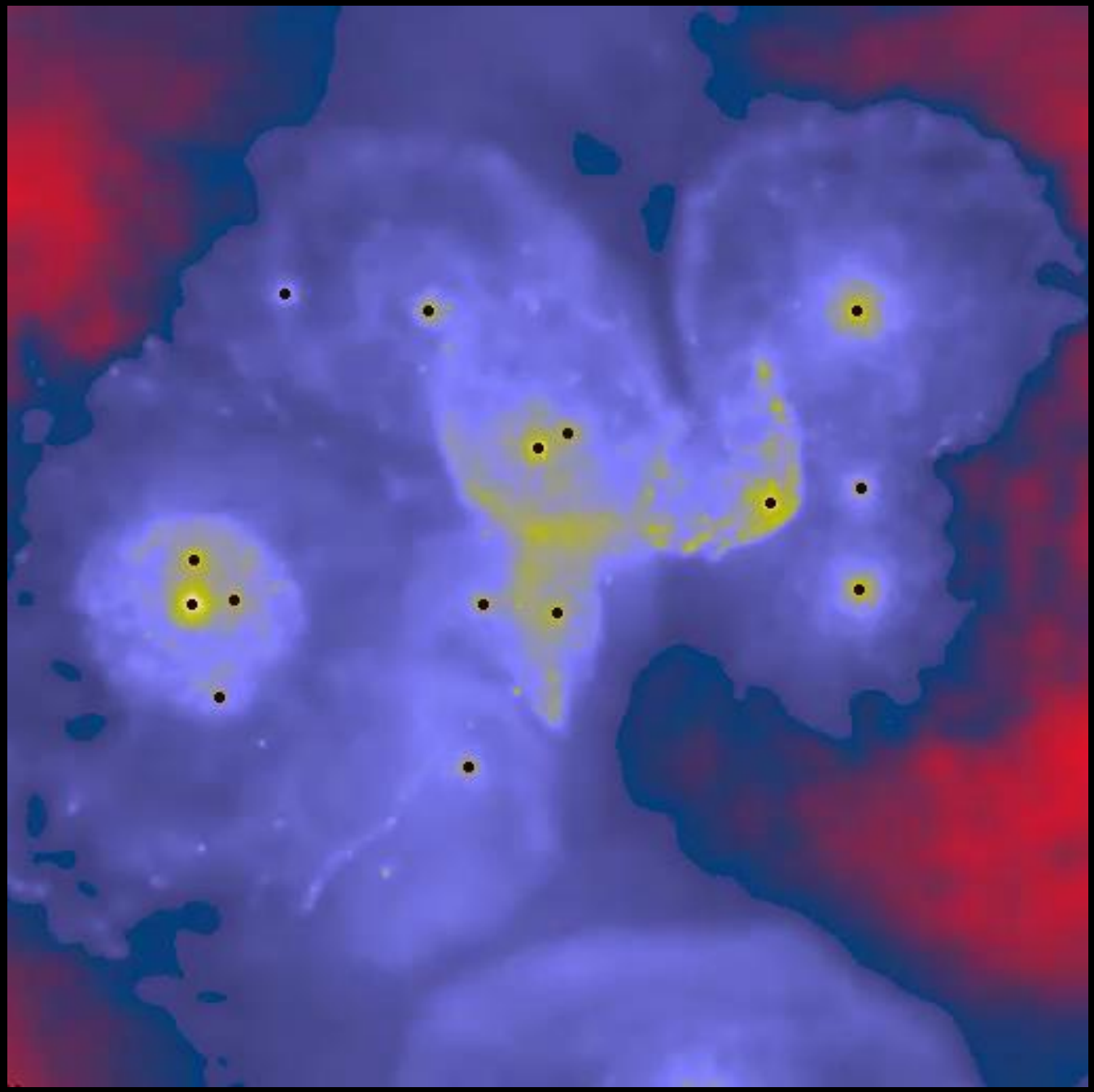
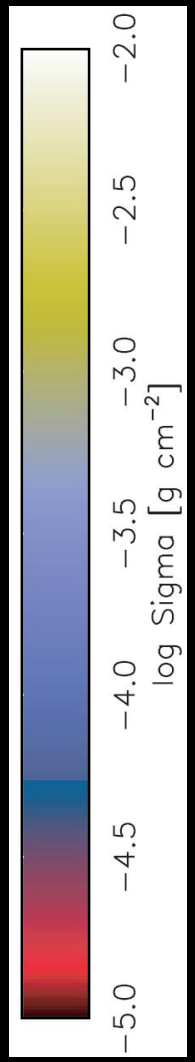


Movie frame: t=500 yr (600 yr ago)

Column Density

(Cuadra+08)

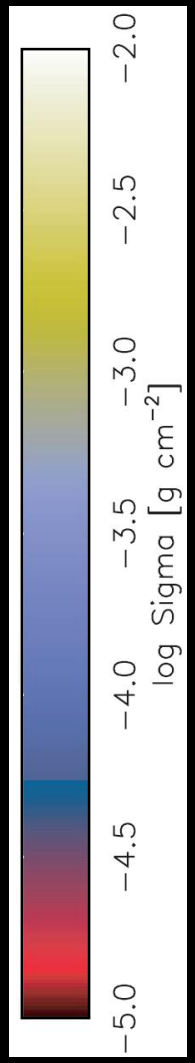


12x12”
~1x1 pc

Movie frame: t=800 yr (300 yr ago)

Column Density

(Cuadra+08)

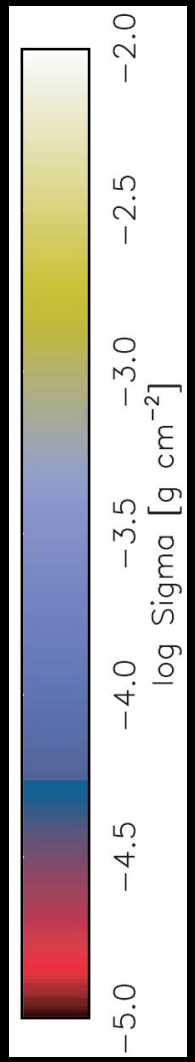


12x12”
~1x1 pc

Movie frame: t=1100 yr (0 yr ago)

Column Density

(Cuadra+08)



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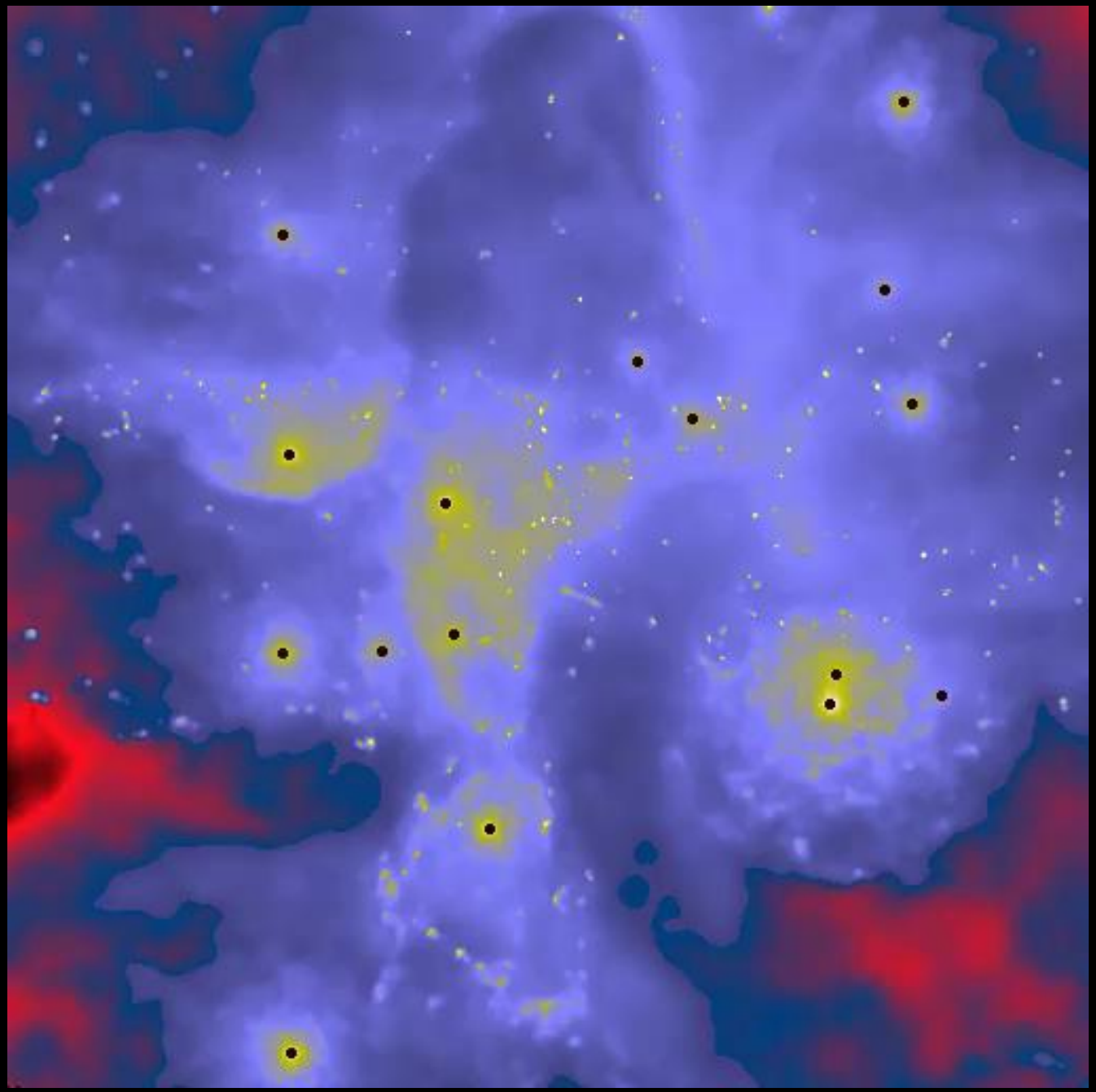

Column Density

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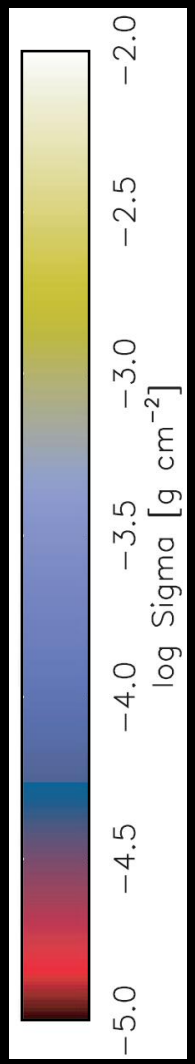
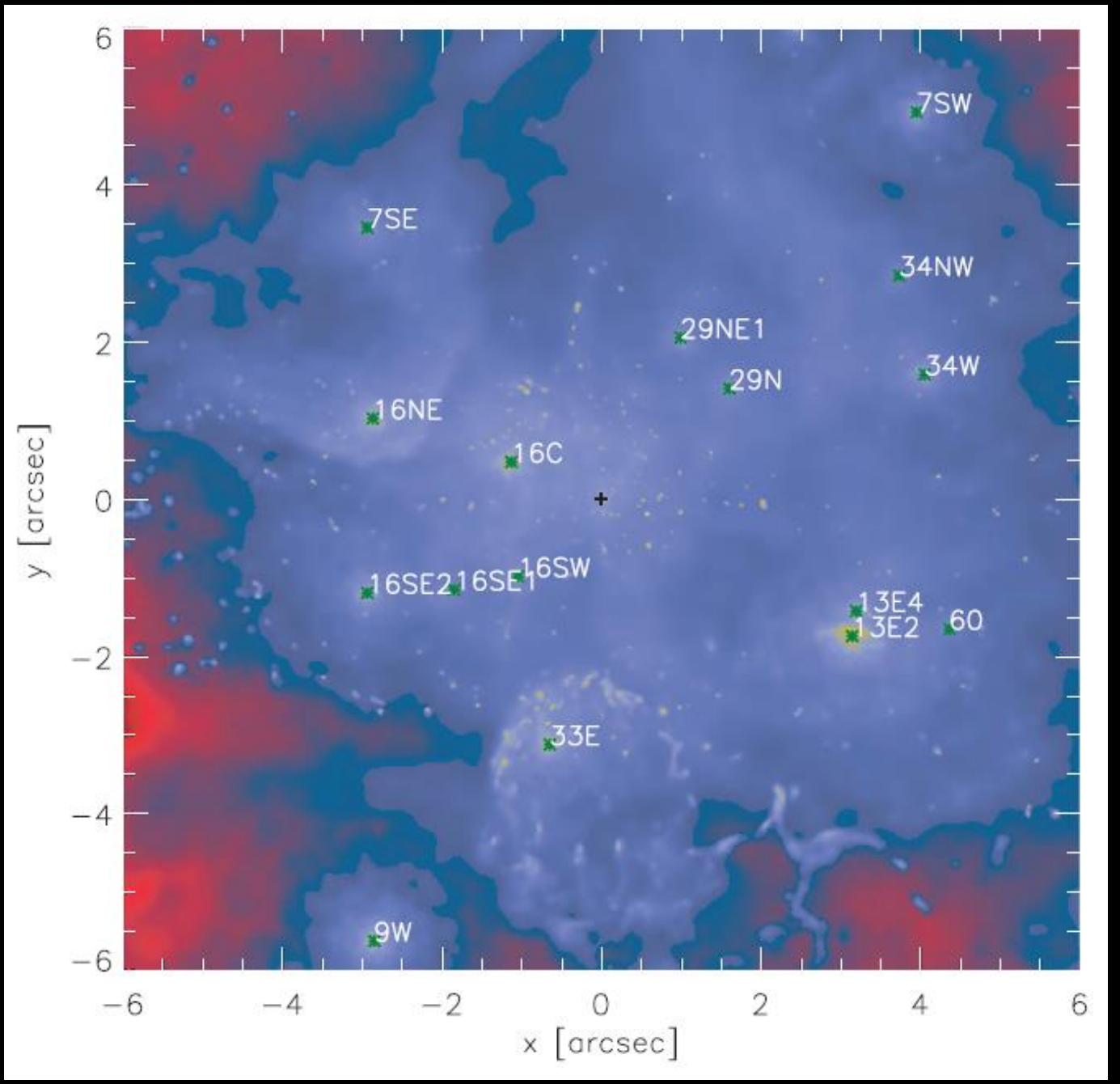
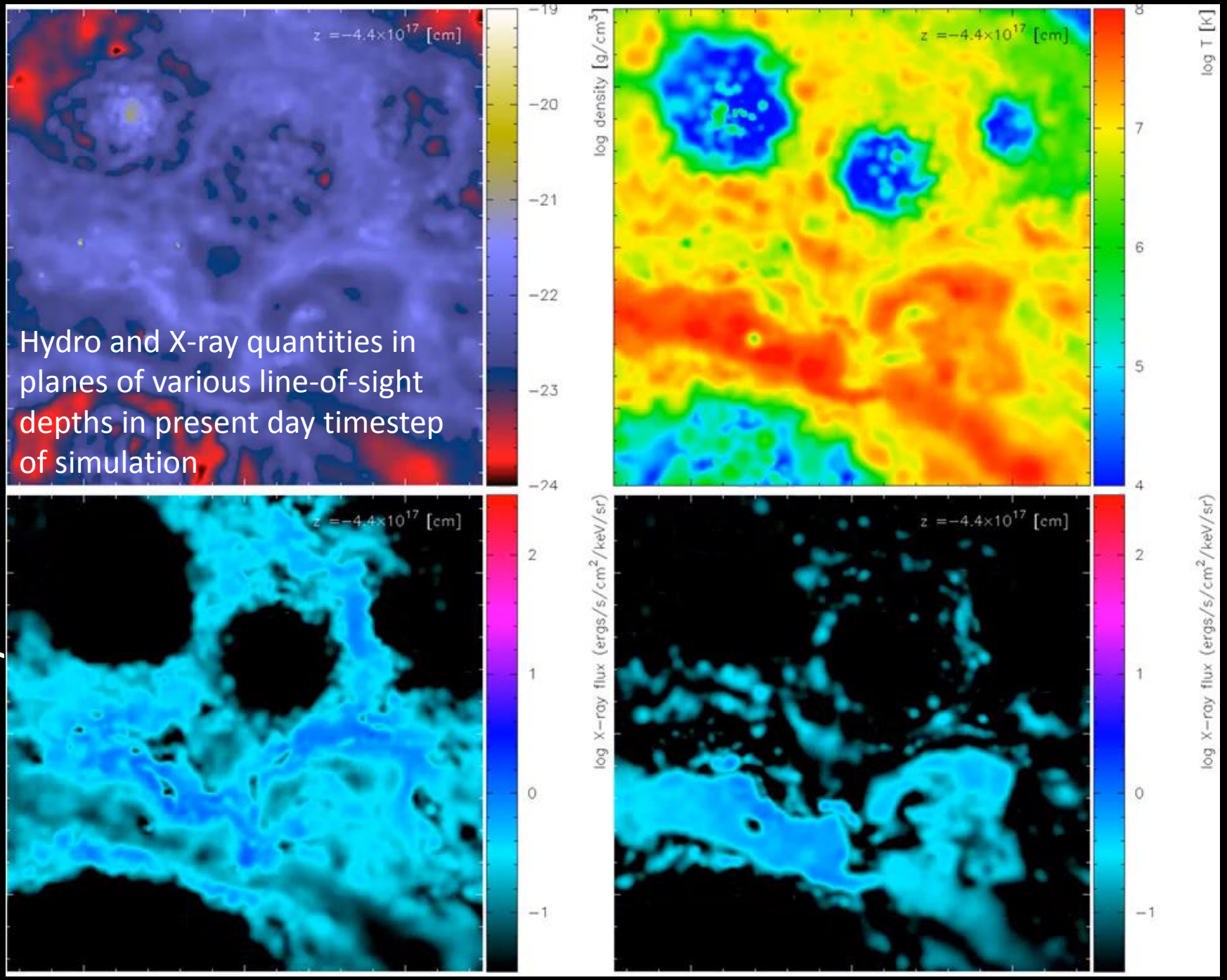
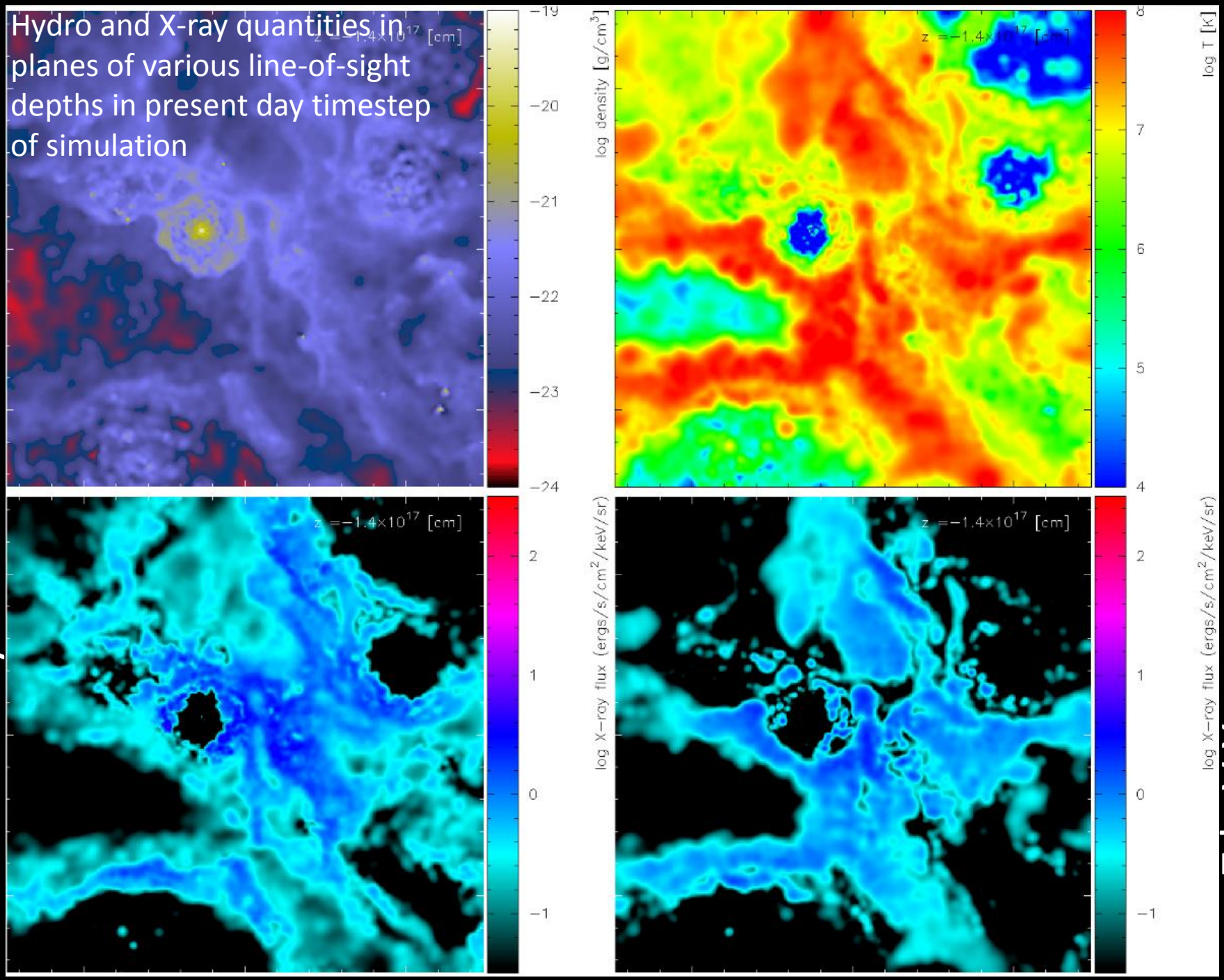
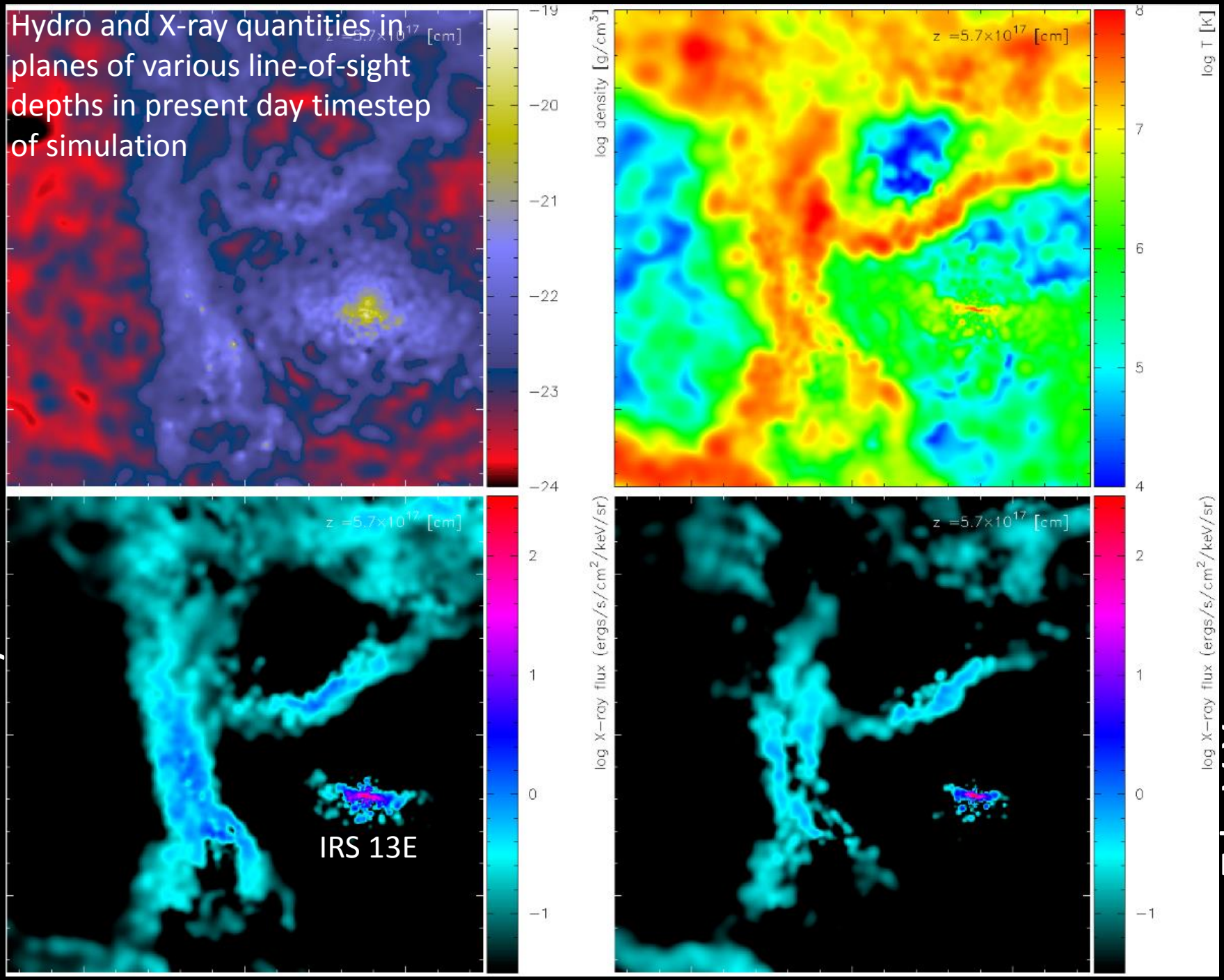





ρ
T
12" x 12"
2 keV X-rays
7 keV X-rays
Hydro and X-ray quantities in planes of various line-of-sight depths in present day timestep of simulation
z =−4.4×10^17 [cm]
log density [g/cm^3]
log T [K]
log X−ray flux (ergs/s/cm^2/keV/sr)

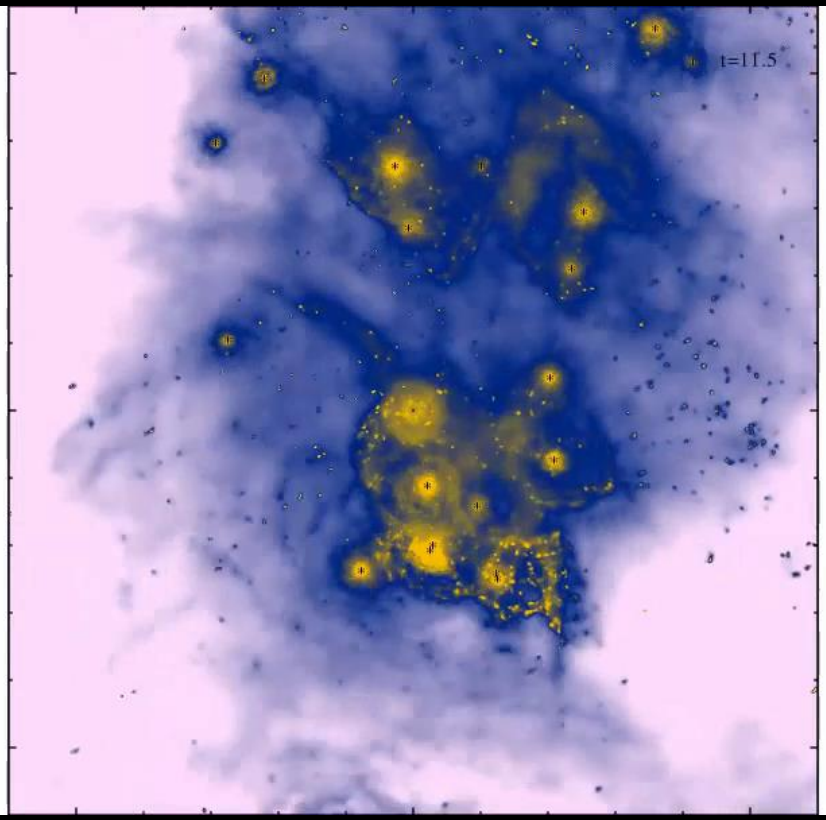

Hydro and X-ray quantities in planes of various line-of-sight depths in present day timestep of simulation
ρ
T
12" x 12"
2 keV X-rays
7 keV X-rays
log density [g/cm³]
log T [K]
log X-ray flux (ergs/s/cm²/keV/sr)
z =−1.4×10¹⁷ [cm]

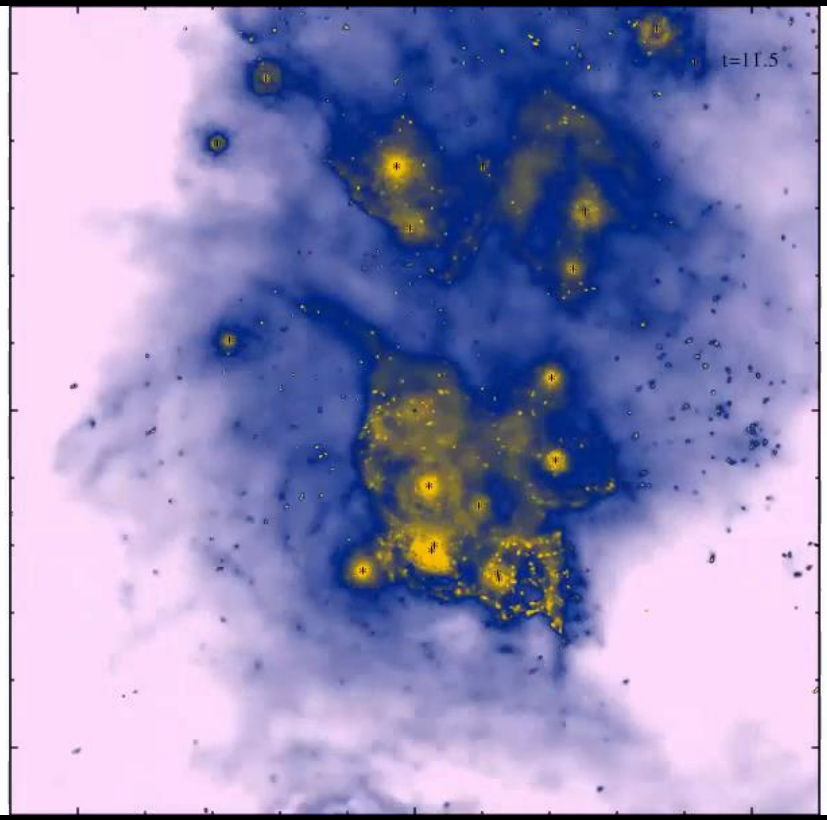

Hydro and X-ray quantities in planes of various line-of-sight depths in present day timestep of simulation
ρ
T
12" x 12"
2 keV X-rays
7 keV X-rays
IRS 13E
z =5.7×10^17 [cm]
log density [g/cm^3]
log T [K]
log X-ray flux (ergs/s/cm^2/keV/sr)

Movie frame: t=400 yr ago, start of outburst

Sgr A* Outflow
(Cuadra+15)

radiatively inefficient accretion flow (RIAF) (Wang+13)
increased X-ray activity in past (Ponti+10)





v_out = 5,000 km/s

v_out = 10,000 km/s

medium

Mdot_out = 1e-4 M_{sun}/yr
t_out = 400 to 100 yr ago

strong

Movie frame: t=300 yr ago, 100 yr into outburst

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(Cuadra+15)

radiatively inefficient accretion flow (RIAF) (Wang+13)
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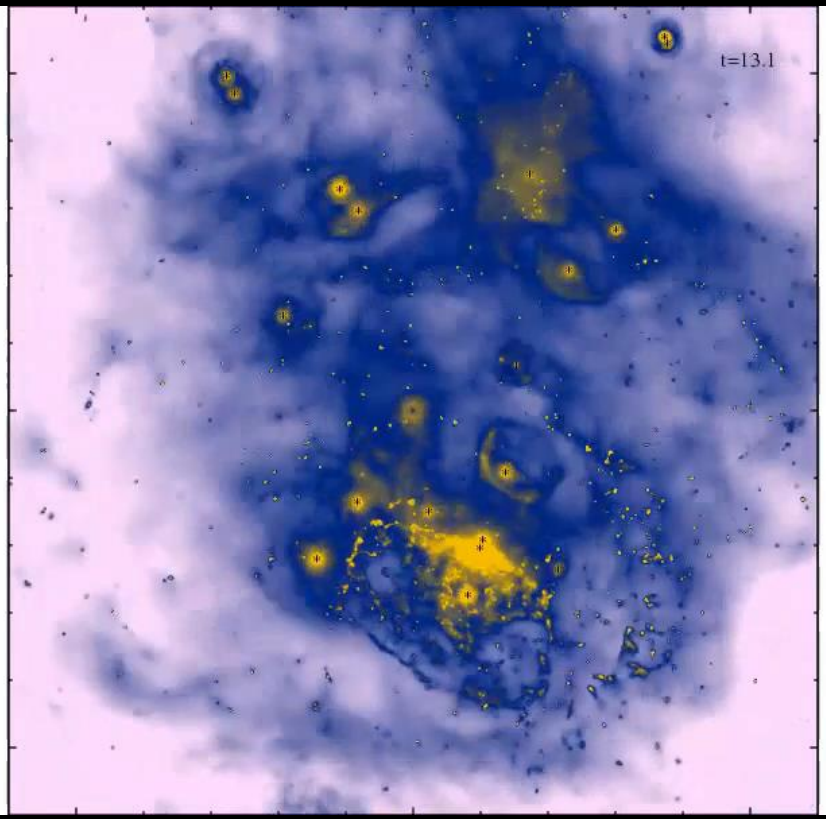

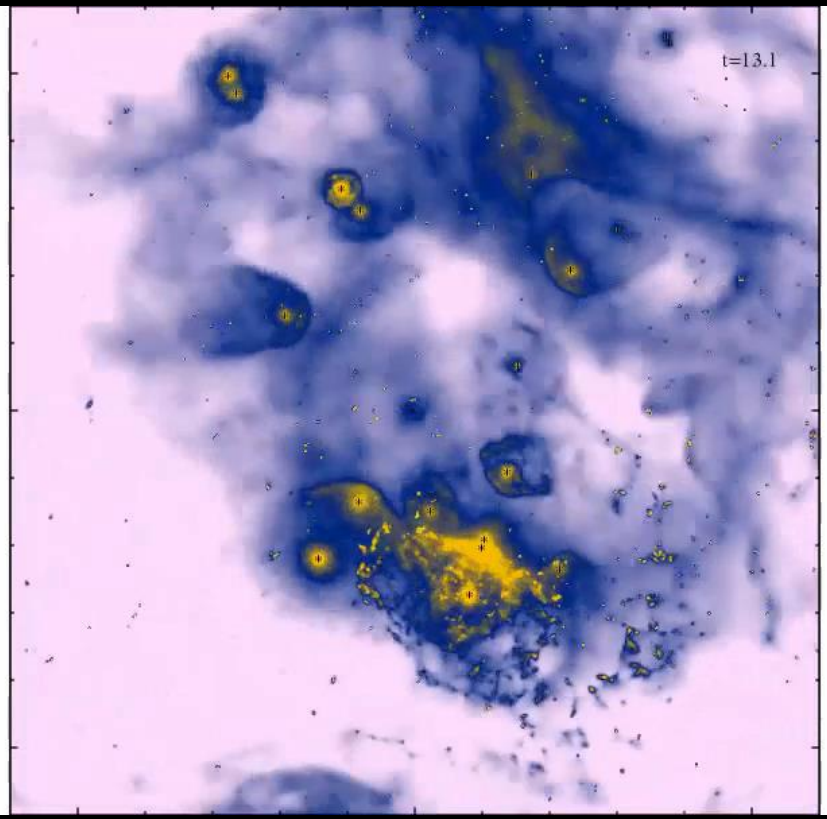

v_out = 5,000 km/s

v_out = 10,000 km/s

medium

Mdot_out = 1e-4 M_{sun}/yr
t_out = 400 to 100 yr ago

strong

Movie frame: t=200 yr ago, 200 yr into outburst

Sgr A* Outflow
(Cuadra+15)

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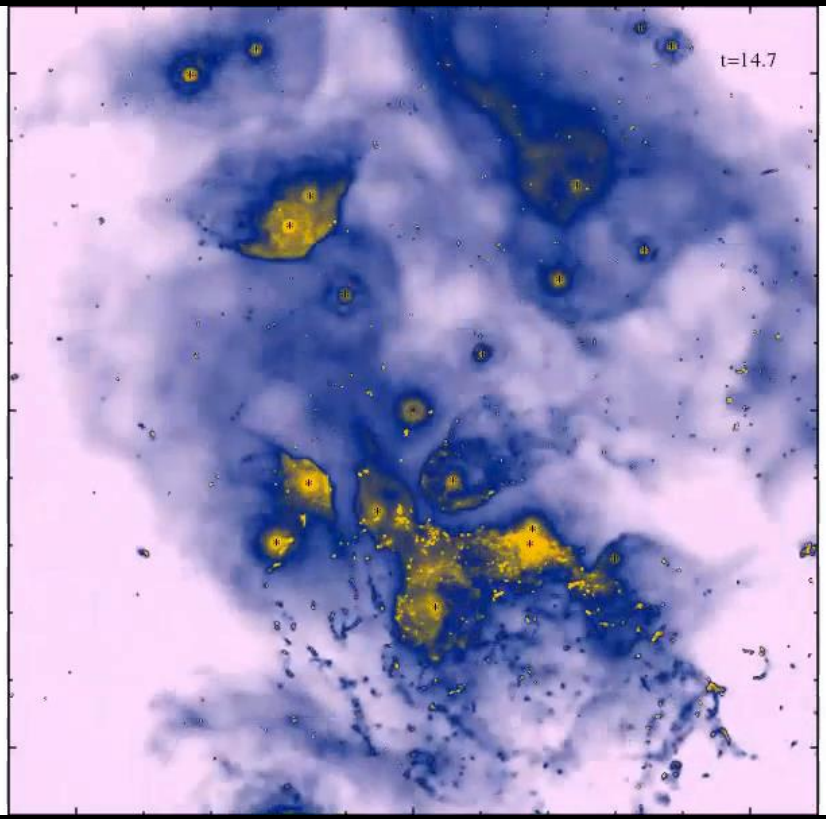

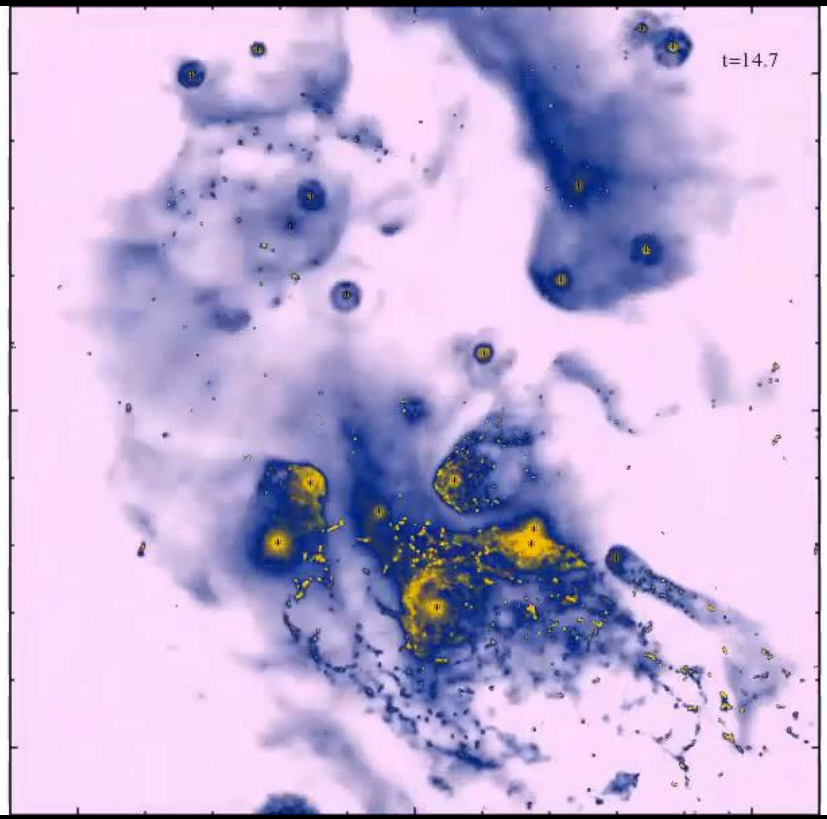

v_out = 5,000 km/s

v_out = 10,000 km/s

medium

Mdot_out = 1e-4 M_{sun}/yr
t_out = 400 to 100 yr ago

strong

Movie frame: t=100 yr ago, end of outburst

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(Cuadra+15)

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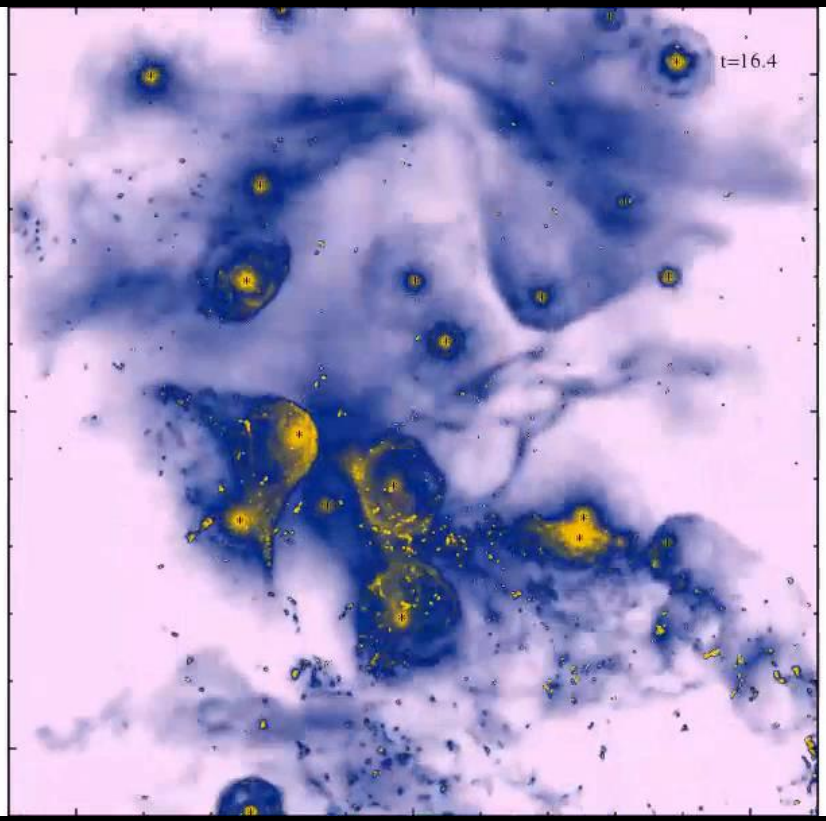

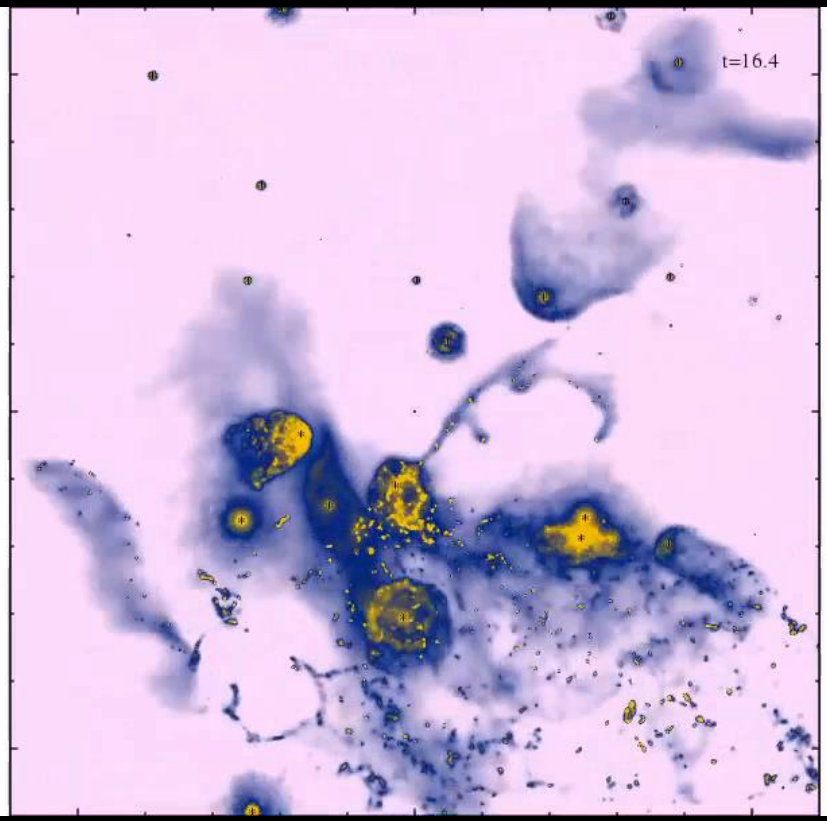

v_out = 5,000 km/s

v_out = 10,000 km/s

medium

Mdot_out = 1e-4 M_{sun}/yr
t_out = 400 to 100 yr ago

strong

Movie frame: t=0 yr ago, 100 yr since outburst ended

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(Cuadra+15)

radiatively inefficient accretion flow (RIAF) (Wang+13)
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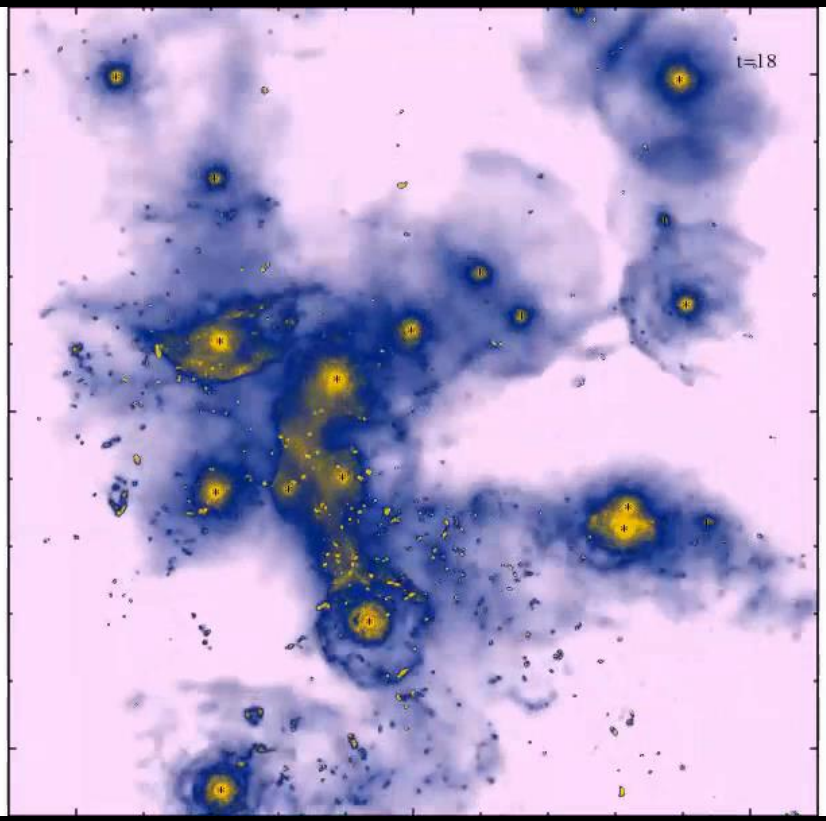
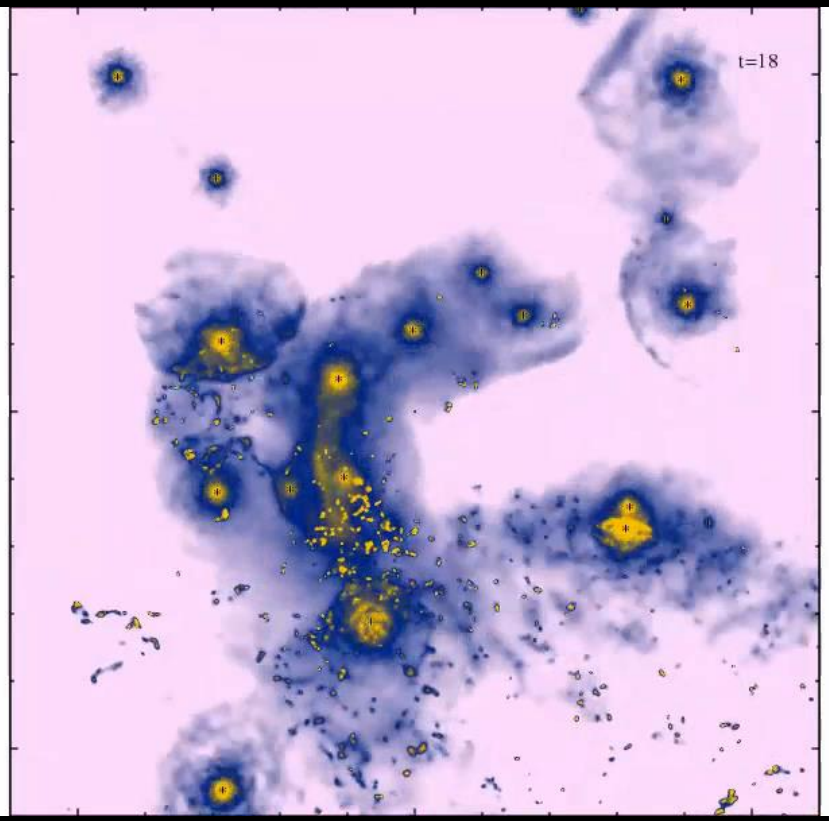




v_out = 5,000 km/s

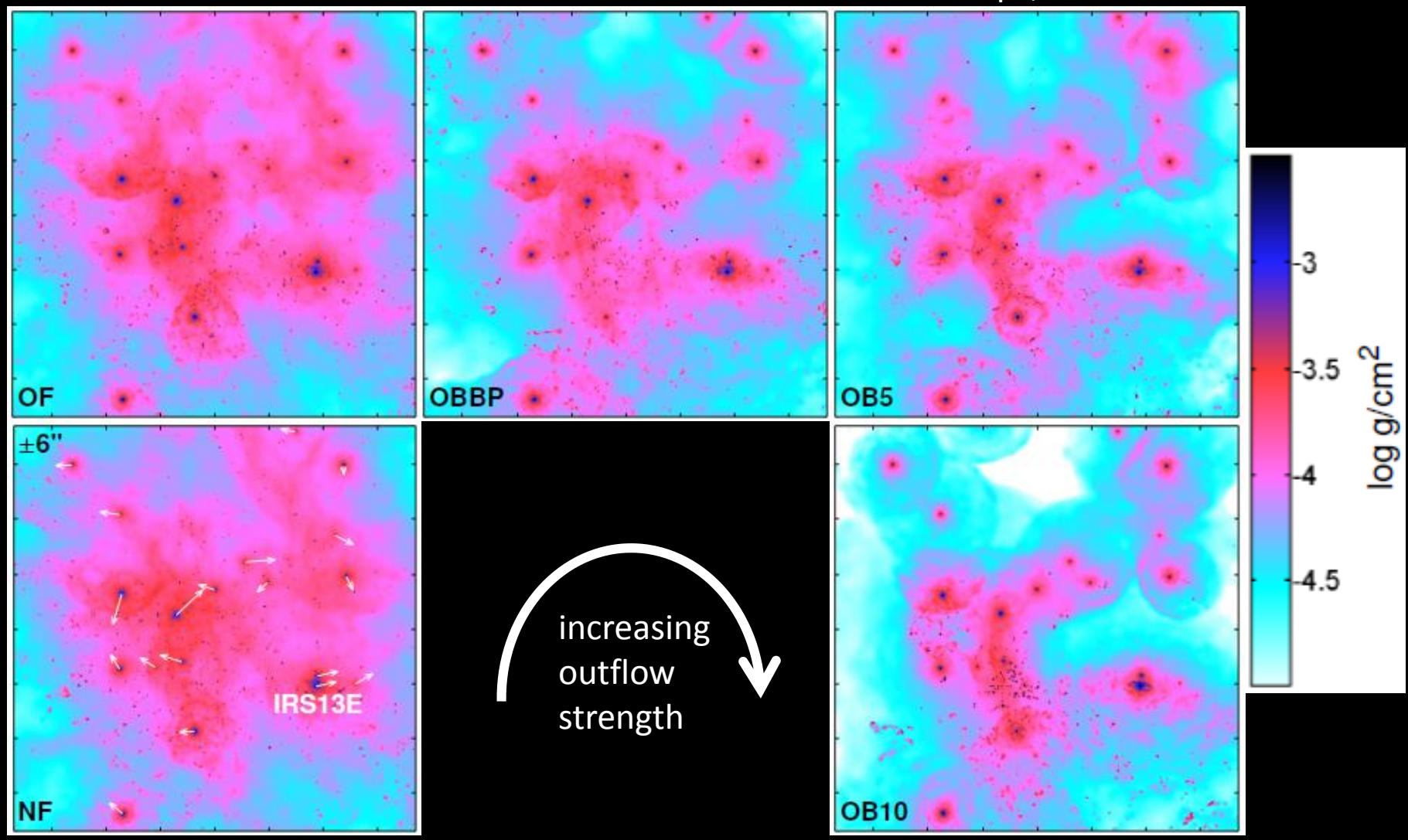
v_out = 10,000 km/s

medium

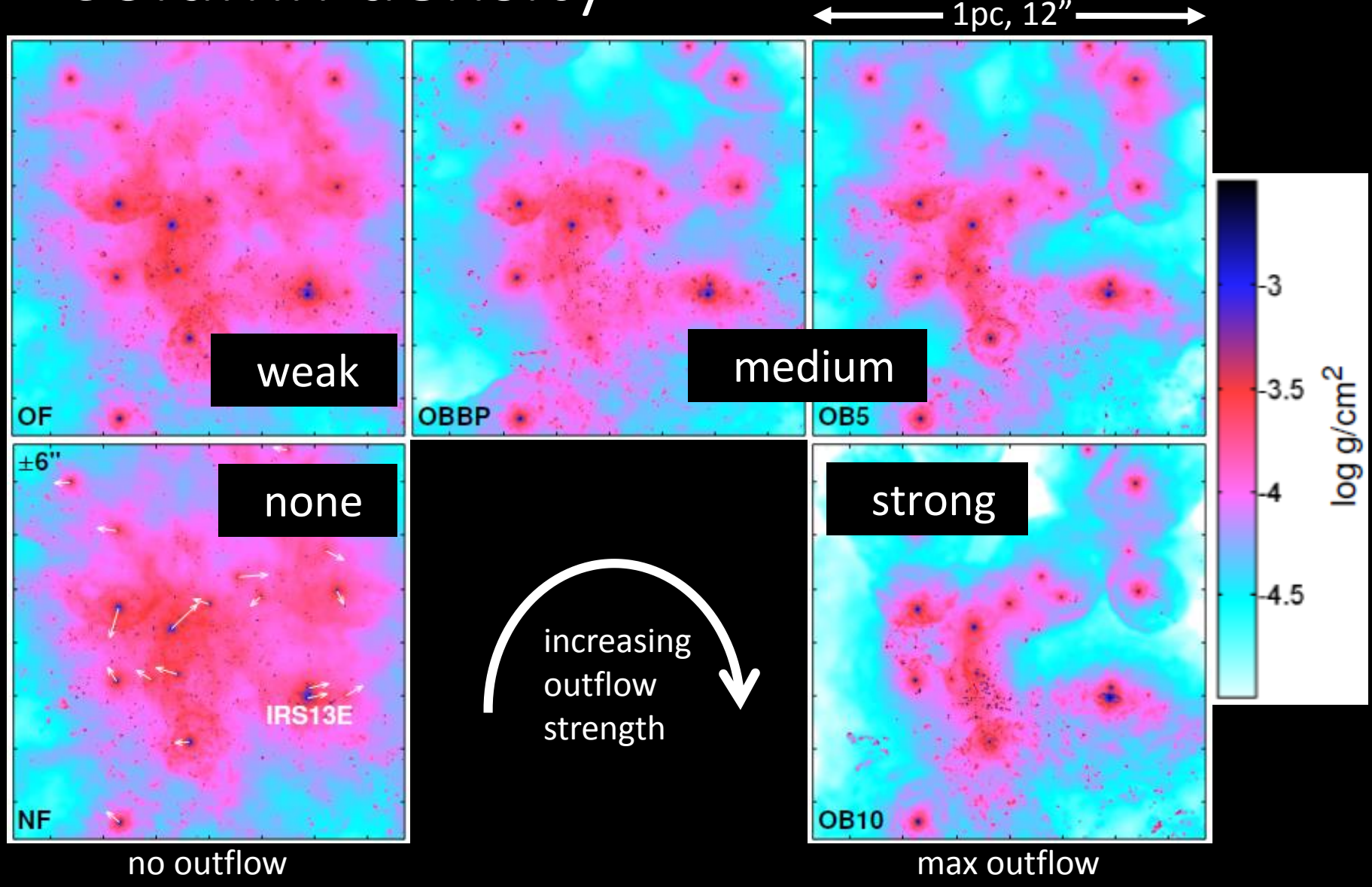
Mdot_out = 1e-4 M_{sun}/yr
t_out = 400 to 100 yr ago

strong

Column density



Column density



X-ray Calculation (Russell13)

- Sum emissivities along 1D rays through simulation
  - Well into optically thin limit, so don't need to solve formal solution to radiative transfer
- Radiative transfer program basis: `SPLASH` (Price07), SPH visualization code

- Emissivity: `APEC` (Smith+01) from `XSpec` (Arnaud+97)
- Opacity: `windtabs` (Leutenegger+10)
- ISM Opacity: `TBabs` (Wilms+00) from `XSpec`

X-ray Calculation (cont.)

- Abundances:
  - WN8-9 & Ofpe/WN9: CMFGEN models
    http://kookaburra.phyast.pitt.edu/hillier/web/CMFGEN.htm
  - WN5-7: Onifer+08
  - WC8-9: Crowther+07

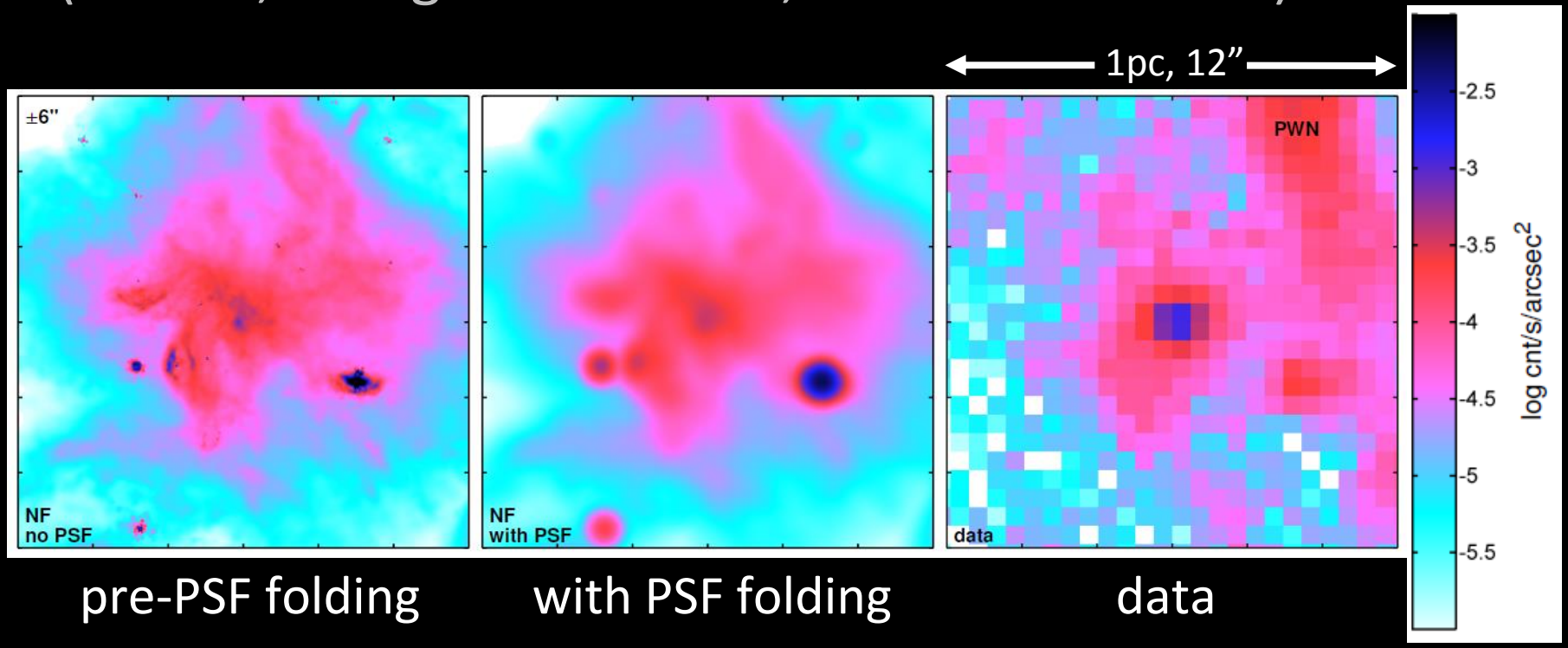
- Response Function Folding: ACIS-S/HETG 0^{th} order
- PSF Folding: 0.5” FWHM Gaussian

  -> Direct comparison with observations

  one free parameter: n_H (ISM absorbing column)

X-ray Image: Models vs. Data

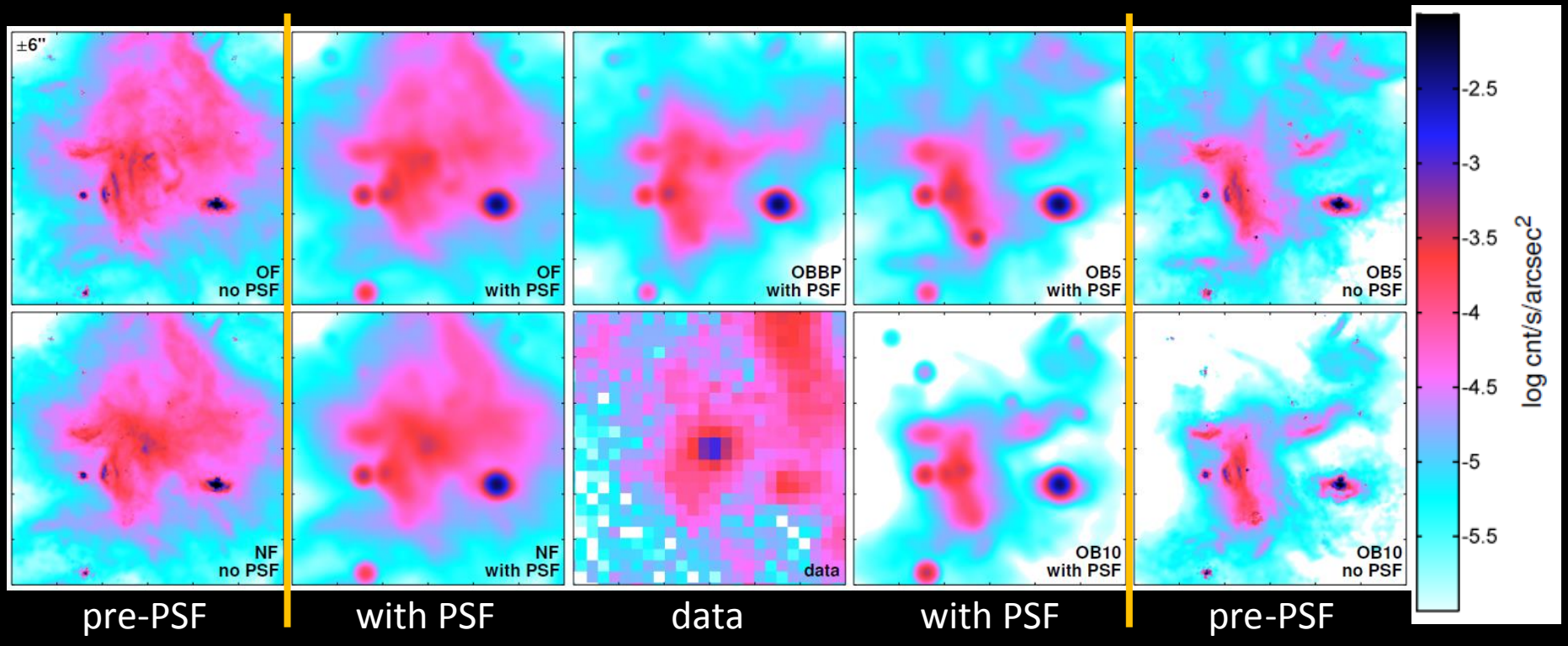
(Russell, Wang & Cuadra 16, arXiv:1607.01562)



pre-PSF folding with PSF folding data

4-9 keV ACIS-S/HETG 0th order, no-outflow model

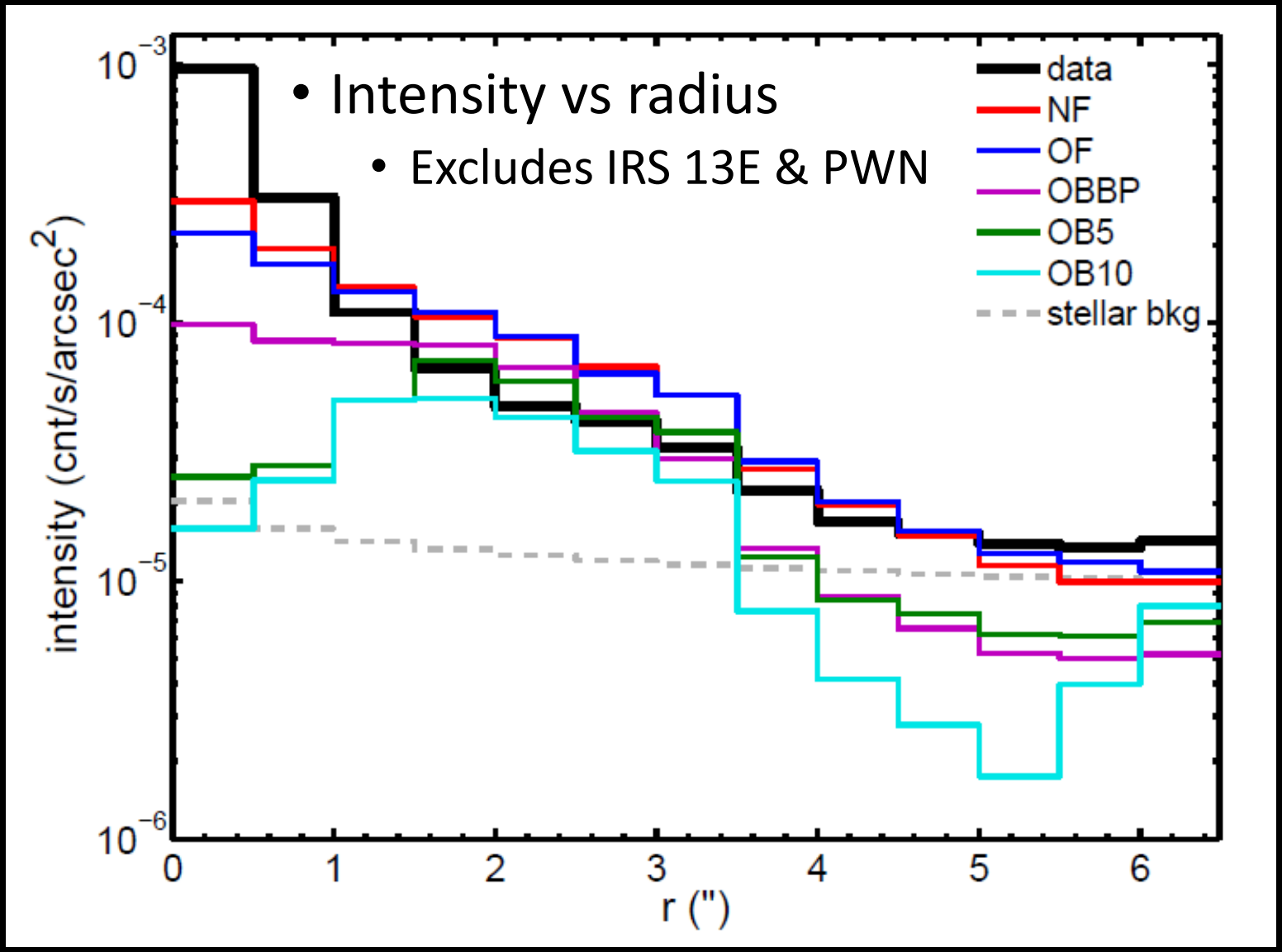
X-ray Image: Models vs. Data
(Russell+16)



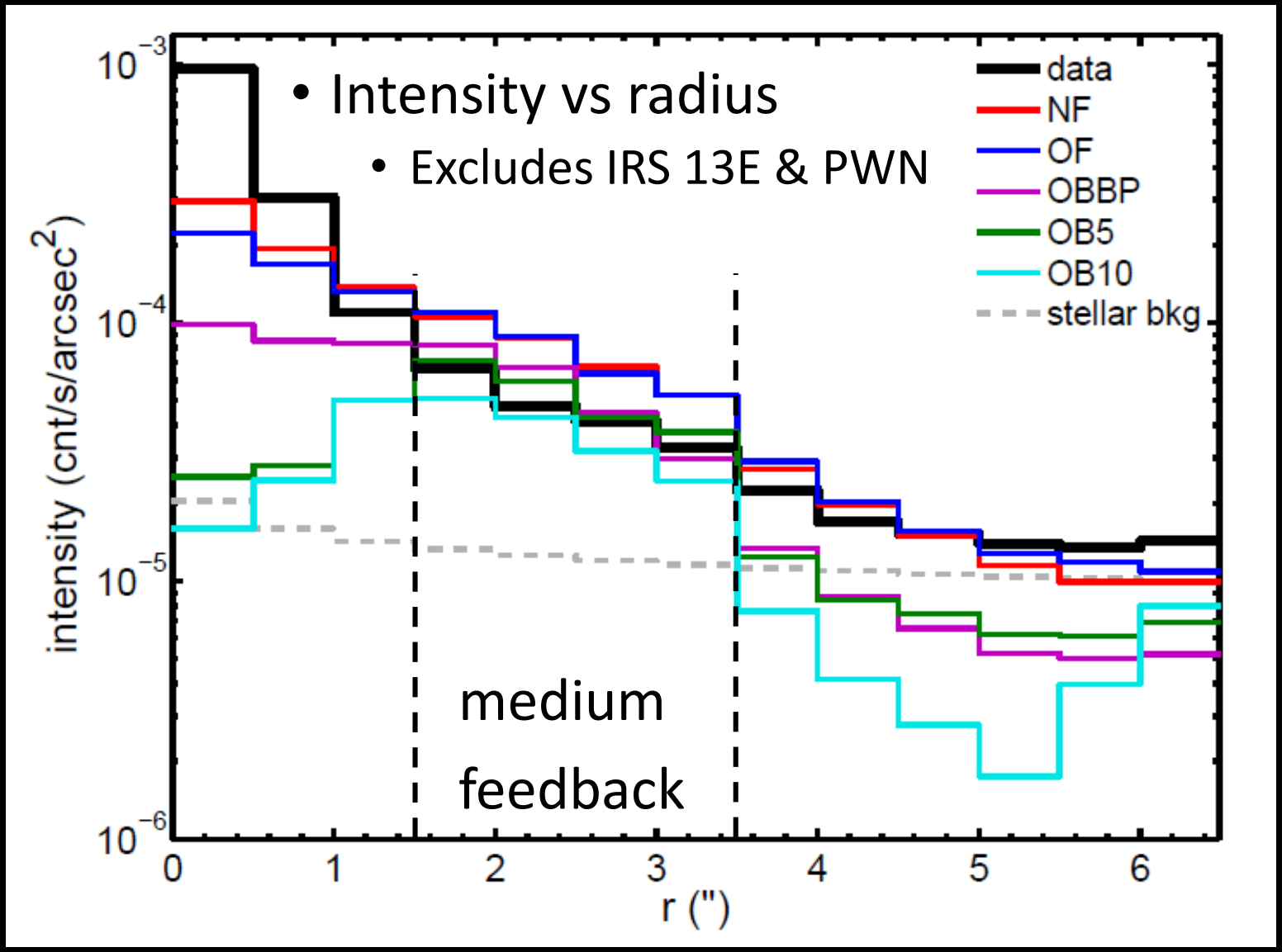
4-9 keV
ACIS-S/HETG
0th order

increasing outflow strength

X-ray Image: Models vs. Data
(Russell+16)



X-ray Image: Models vs. Data
(Russell+16)



X-ray Image: Models vs. Data
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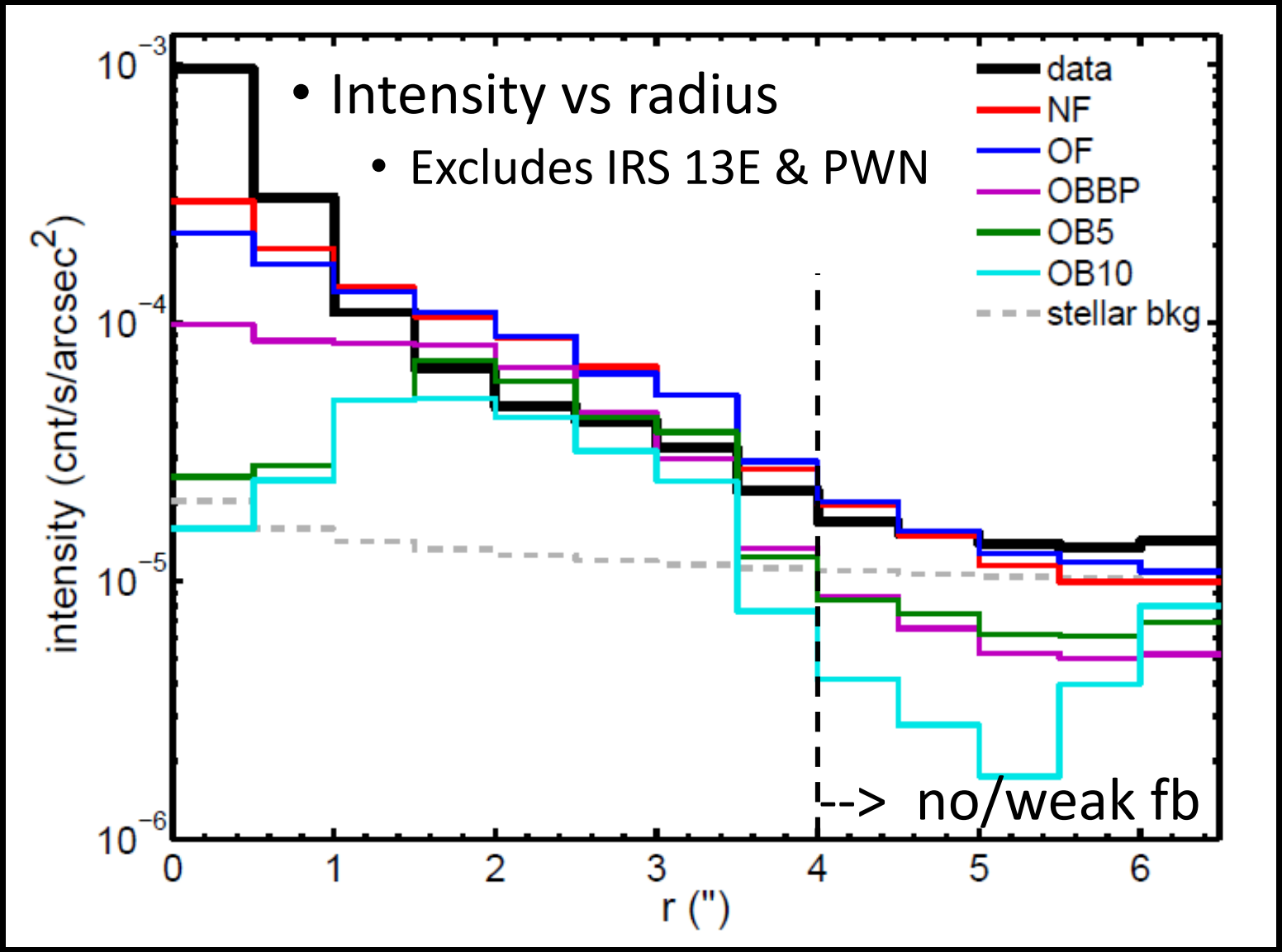

X-ray Image: Models vs. Data
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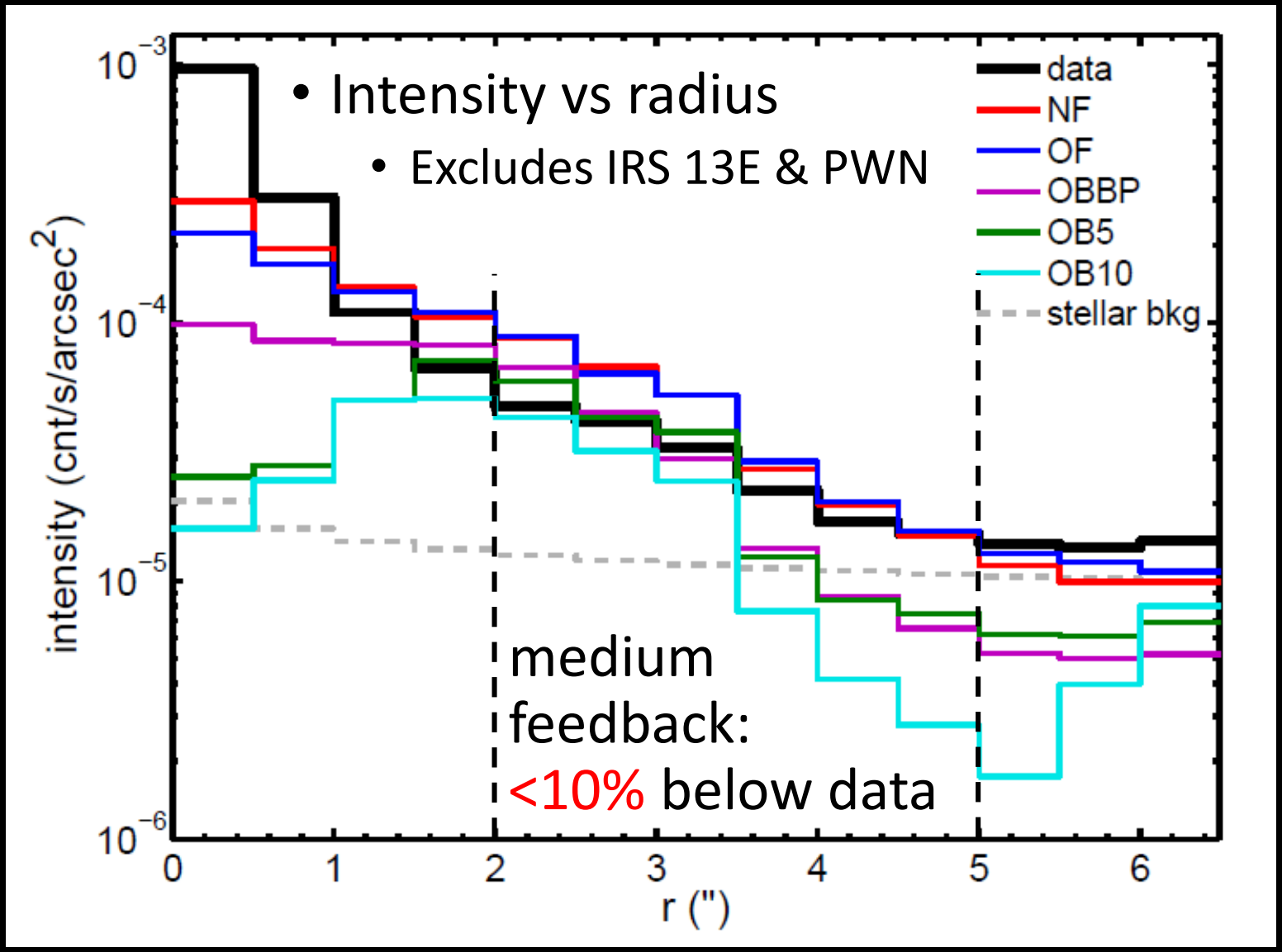
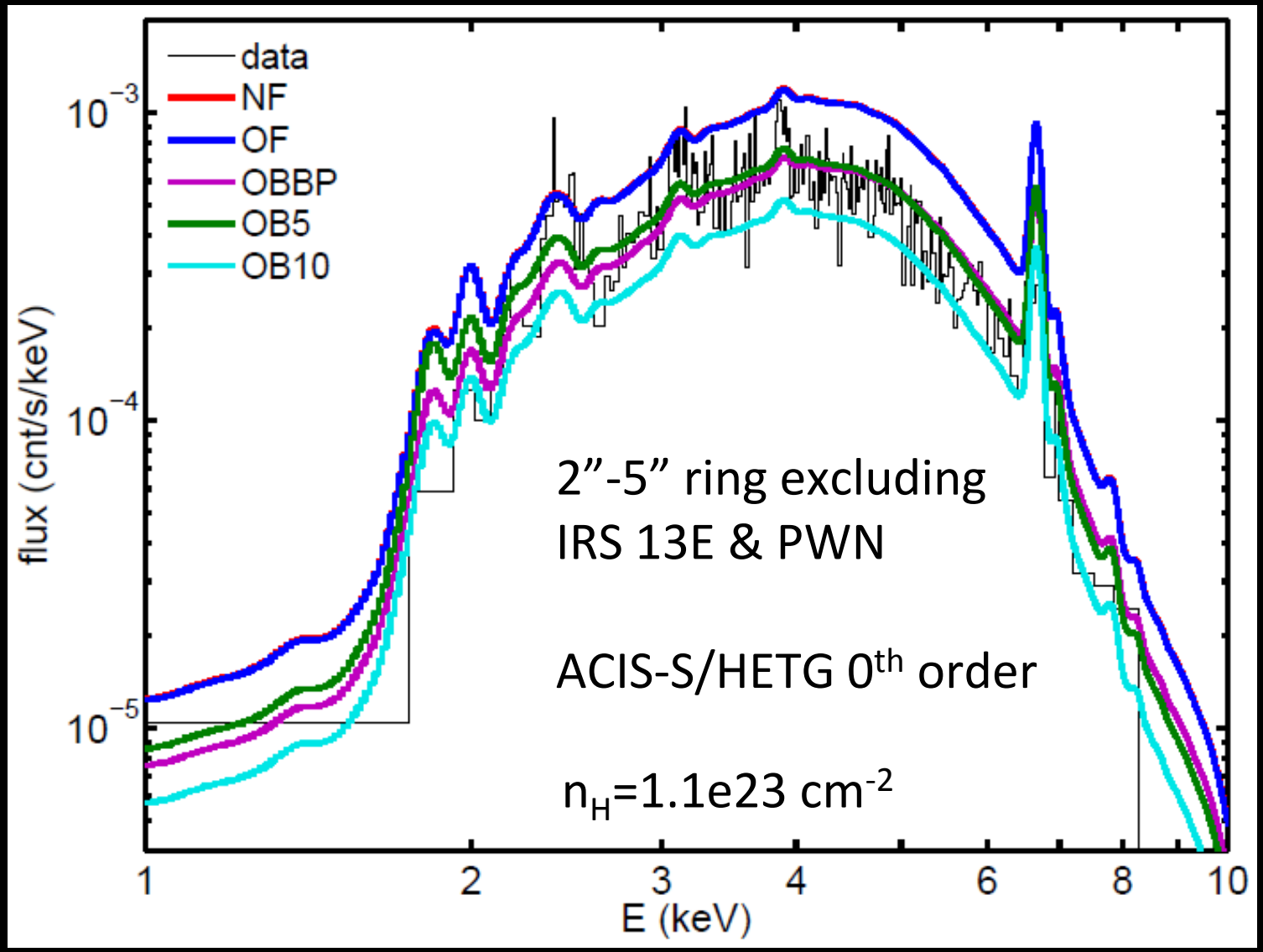
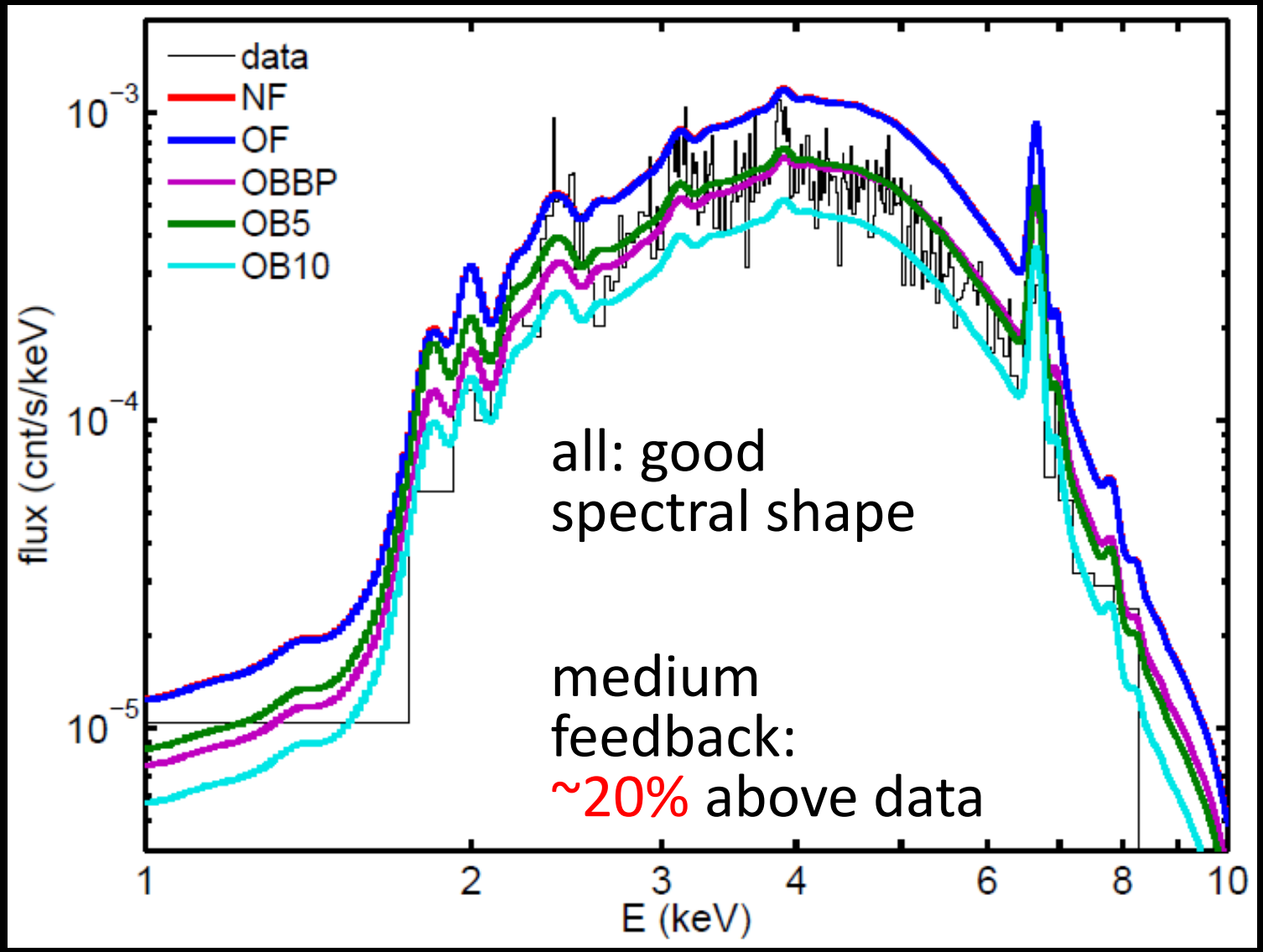


X-ray Spectra: Models vs. Data
(Russell+16)



X-ray Spectra: Models vs. Data
(Russell+16)

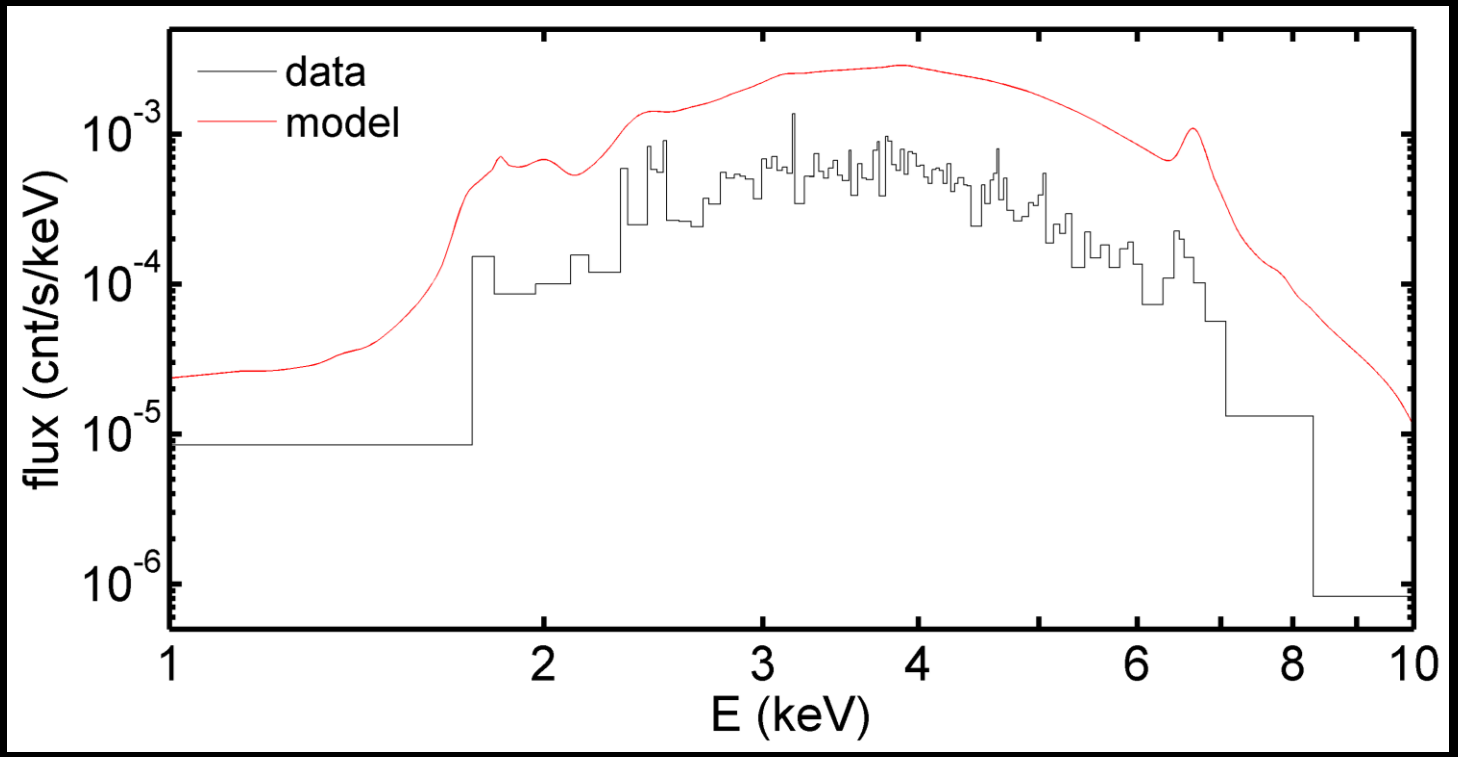


Summary

- 3D Hydro + Radiative Transfer ->
  Model X-ray observation of Galactic center
- Sgr A* outflow affects current diffuse X-ray emission
- Spectral shape: well reproduced ->
  shocked WR winds produce diffuse X-ray emission
- Flux level: within 20% for 2”-5” over 4-9 keV for
  medium feedback

Future Work: weaken IRS 13E winds

(Wang+ in prep)



- Model too hard → lower wind speeds
  too much flux → lower mass-loss rates
- WC: IR spectra modeling subject to dust contamination
  - reduce wind strength to other WCs in Galactic center
- WN: lower wind strength (Yusef-Zadeh+15)

Future Work: Additional elements

- O stars (Cocker & Pittard 05)
  - Increase WR-wind emission
- ‘S’ stars (Lutzgendorf+16)
  - Alter accretion flow of WR material onto Sgr A*
- Mini-spiral & circumnuclear disk
  - Constrain gas → increase emission in outer regions
  - Alleviate r<3.5” and r>4” discrepancy?

- Improved hydrodynamic method (see Calderón poster)
  - Pressure entropy SPH (Saitoh&Makino13, Hopkins13)
  - Mesh-free method GIZMO (Hopkins15)

Extra Slides

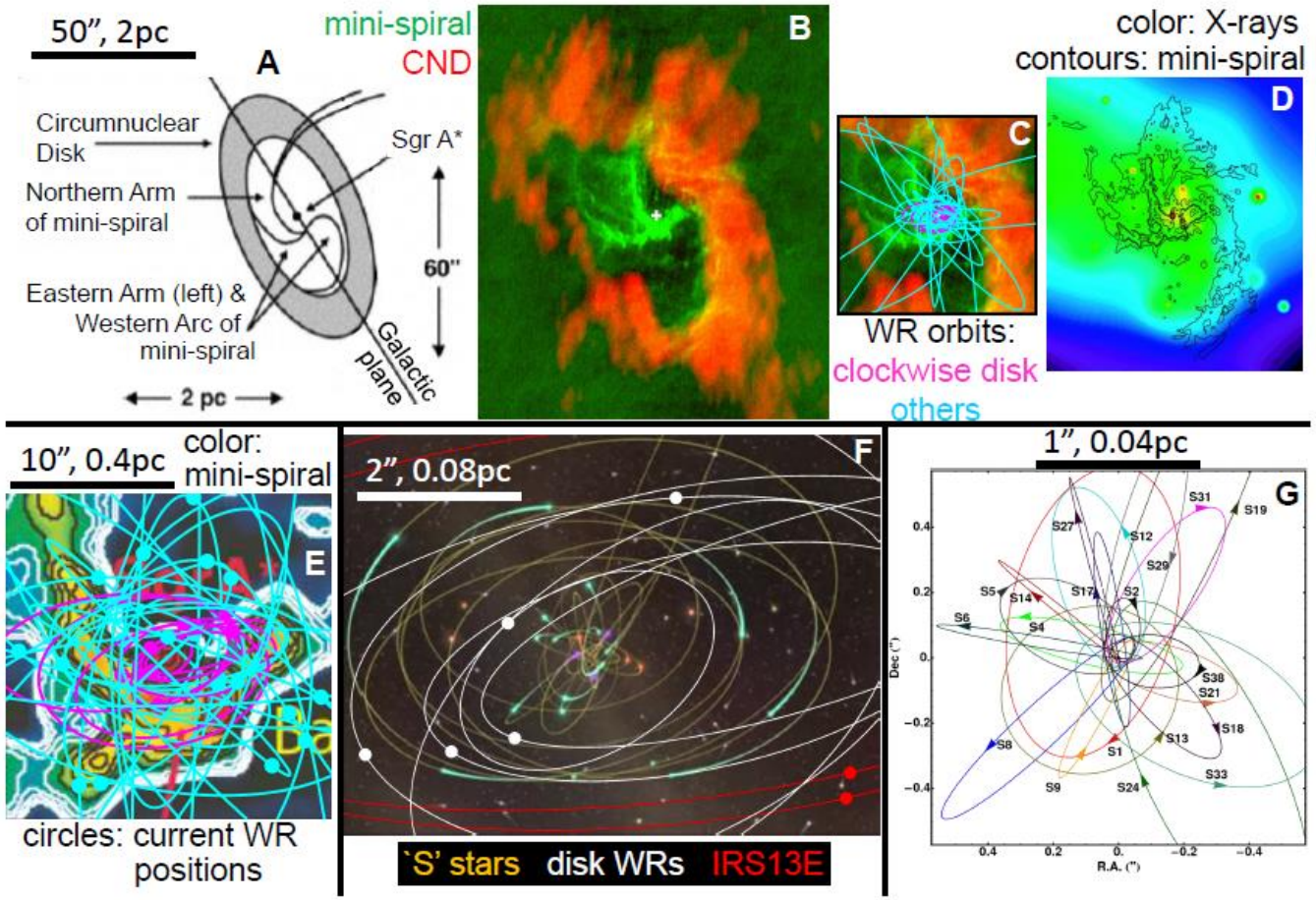


Figure 1: Observations reveal the complex structure of the Galactic center on different physical scales. *A*: schematic modified from Baganoff et al. (2003). *B*: HCN 1-0 emission (red) showing the CND and 3.6 cm radio emission (green) highlighting the mini-spiral. *C*: WR orbits (magenta for clockwise-disk stars, cyan for others) overlayed on inner region. *D*: X-rays (color) showing the hot gas and 6 cm radio (contours) locating the mini-spiral. *E*: WR orbits and current positions (circles) overlayed on 100GHz ALMA observations showing the mini-spiral. *F*: WR orbits of disk stars (white) overlayed on 'S'-star orbits (yellow), along with the two WRs in the IRS 13E cluster (red). *G*: all 'S' stars that have been observed for a full orbit. References: Baganoff et al. (2003), Cuadra et al. (2008), Ferrière (2012), Gillessen et al. (2009), Paumard et al. (2006), Tsuboi et al. (2016), and Yelda et al. (2014).

Model/Data ratios: 4-9 keV, 2”-5”

- NF, OF, OBBP, O5, O10
- 1.968 1.957 1.210 1.204 0.807 from spectra
  (background of 6"-18" ring)
- 1.500 1.492 0.922 0.918 0.615 from image
  (background of CV's that Daniel calculated)

- 1.734 1.725 1.066 1.061 0.711 mean
  (spectra + image)/2

WR Abundances

	X_{H}	X_{He}	X_{C}	X_{N}	X_{O}
WC8-9	0	60	31	0	7
WN5-7	0	98.5	0.029	1	0.018
WN8-9 & Ofpe/WN9	11.5	82.4	0.0124	1.15	0.066

mass fractions (%)